Internal Circulation in Tidal Channels and Straits
and
Internal Circulation in Tidal Channels and Straits: A Comparison of Observed and Numerical Turbulence Estimates (AASERT)

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Grant Number: N00014-97-1-0012 AASERT award #: N00014-97-1-0625
http://www.ccalmr.ogi.edu/res_act.html

LONG-TERM GOAL

The principal long-term objectives of this project and its associated AASERT are to provide:

- a 3-D conceptual understanding of circulation and scalar transport in the numerous estuaries and straits worldwide with both strong tides and buoyancy forcing,
- improved analysis methods based on continuous wavelet transforms for defining the non-stationary and non-linear processes that drive circulation in these environments, and
- in concert with related projects, an improved understanding of vertical turbulent mixing processes in stratified estuarine flows.

SCIENTIFIC OBJECTIVES

Present work focuses on the 3-D distribution of the along-channel circulation, hydraulic control and mixing at the estuary entrance, salt and suspended particulate transport (SPM) in stratified flows, and near-bed and interfacial mixing processes in stratified environments. Specific objectives include:

- test a 3-D mixed analytical/numerical circulation model for sub-areas of the Columbia River estuary, to calculate tidal and residual flow during periods for which data are available;
- examine hydraulic control effects near the mouth of the Columbia River using a three-layer model that includes mixing between layers and bed dissipation;
- analyze near-bed and interfacial turbulent momentum, salt and sediment flux data to better understand vertical fluxes of momentum, salt and sediment in stratified environments;
- develop and disseminate to the oceanographic community wavelet transform tidal analysis and turbulence estimation tools; and
- use wavelet and other tools to analyze key data sets.

APPROACH

This project takes a unified approach to analyzing the effects of buoyancy on estuarine and shelf tides and scalar transport, as funded by the Coastal Dynamics Program of ONR and the National Science Foundation (NSF) Land-Margin Ecosystem Research (LMER) Program. In all environments of interest, a time-varying density field leads to markedly unsteady tidal flow, which in turn feeds back onto the density field through tidal straining and variable mixing. Scalar transports then depend on the detailed correlations of time-dependent velocity and scalar fields and on vertical turbulent mixing. On a

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**
4. TITLE AND SUBTITLE **Internal Circulation in Tidal Channels and Straits and Internal Circulation in Tidal Channels and Straits: A Comparison of Observed and Numerical Turbulence Estimates (AASERT)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Oregon Graduate Institue,Center for Coastal and Land-Margin Research,Portland,OR,97291-1000**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002252.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

functional level, these efforts have been augmented over the last two years through data collected by the ONR-funded Oceanographic and Environmental Characterization of Coastal Regions (OECCR). The CORIE nowcast-forecast system developed through OECCR provides a large data set that requires interpretation. The understanding that is being developed through the tidal channels project can be transferred to other environments world-wide, just as can the OECCR modeling and forecast methods.

WORK COMPLETED

1. Acoustic Doppler profiler (ADP) backscatter has been calibrated and used to calculate suspended particulate material (SPM) concentration and horizontal transport, providing an understanding of the seasonal variations in SPM transport associated with changes in flow and tidal range (Jay).

2. Estimates of key turbulence parameters for near-bed and interfacial locations have been made at all stages of the tide at mid-estuary locations. Time series of TKE, stress components, dissipation and buoyancy flux have been calculated. Acoustic backscatter from a Sontek field acoustic Doppler velocimeter (ADV) has been calibrated and used to calculate vertical sediment fluxes and interpret estuarine suspended sediment processes (D. J. Kay). Mr. Kay will defend his thesis 4 December 1998.

3. The semi-analytical model of estuarine circulation has been completed, tested against selected data sets and used to investigate the effects of typical topographies on mean and tidal circulation (J. D. Musiak and D. A. Jay). Mr. Musiak has defended his thesis and will graduate in December 1998.

4. A three-layer, laterally averaged model with interfacial mixing and bedstress has been constructed and tested through joint ONR and LMER support. It has been used to examine hydraulic control, mixing and circulation at the estuary entrance (C. N. Cudaback). The model reproduces typical flood and ebb structures seen in shallow entrances with internal hydraulic controls. Ms. Cudaback received her Ph.D in June 1998 and is now a Post-Doctoral Research Associate at Scripps.

5. Development of continuous wavelet transform (CWT) analyses has been extended to include routines for multiple level, two-component {u,v} rotary analyses (for ADCP current records). Wavelet cross-spectra analyses and methods for unevenly spaced data have been developed (D. A. Jay).

6. We have demonstrated the existence of multiple internal tide generation mechanisms in the Columbia River plume area. In addition to the usual shelf-break mechanism, internal tides strongly coupled with the barotropic tide emanate from the estuary mouth. Internal tide ray paths are being calculated, in an attempt to understand the spatial distribution of internal tides (D. A. Jay).

RESULTS

Stratified Flow over Typical Estuarine Topography (Low Internal Froude Numbers): Traditional estuarine circulation theory following from Hansen and Rattray (1965) has not led to a clear understanding of stratified estuarine flow over topography, because the only tools available were very simple theories for uniform or geometric changes in width and depth (on the one hand) and complex 3-D numerical models (on the other). We have developed and tested (Musiak, 1998) an intermediate, semi-analytic profile model valid for shallow estuaries and low internal Froude numbers (averaged over a tidal cycle). We illustrate here effects of along-channel wind in a stepped (dredged) channel for the cases where the wind strengthens and weakens the two-layer internal circulation (Figure 1).

Hydraulic Control at an Estuary Mouth (High Internal Froude Numbers): Two-layer hydraulic control theory exhibits many features of estuarine circulation, but cannot reproduce the pronounced flood interfacial jet and ebb expansion of the interfacial layer to encompass most or all of the flow. Also typical of

estuarine entrances is the existence of critical or super-critical internal Froude numbers for much of the tidal cycle, so that the above profile model is not useful. Cudaback (1998) has developed a three-layer model that includes bed friction, an explicit interface layer and turbulent entrainment between layers (via the Ellison and Turner, 1959 formulation). The model nicely re-produces the interfacial jet on flood and to a lesser extent the breakdown in layers on ebb.

SPM Transport Processes in Estuarine Turbidity Maxima (ETM): One of the advantages of ADP velocity measurements is that simultaneous determinations of SPM concentration and SPM transport are possible, once the ADP backscatter has been calibrated (in our case by LMER). CORIE ADP time series data provide an ability to examine the response of ETM transport processes to external changes in river flow, SPM supply and tidal range (e.g., Figure 1). This is quite important both for understanding estuarine particle trapping and for the insight it gives to estuarine ecosystem processes based on reprocessing of particulate organics. This work has generated the hypothesis that estuaries amplify climate signals through their SPM budget; this is now being tested under NSF funding.

Wavelet Cross Spectra and Methods for Unevenly Spaced Data: This work addressed two data analysis needs for non-stationary time series. The first issue is an ability to calculate local (in time) quantities analogous to the global coherence and phase estimated via a Fourier transform for entire time series. We have improved Liu's (1994) normalization of the coherence, and developed software in a form useful for ADCP data. The second issue is a need to apply wavelet tidal analyses to time series with gaps. A wavelet analysis is sensitive because of its local nature – any time there is a local correlation between tidal stage and missing data, the filters become unbalanced and leak low frequency energy. These errors can, however, now largely be avoided.

Analyses of Turbulent Processes: These are vital to Tidal Channels modeling, for development of a qualitative understanding of estuarine scalar transport, and for improvement of numerical turbulence algorithms. Acoustic Doppler velocimeter (ADV) technology provides impressive capabilities and can be used in a variety of ways, provided one is aware of its strengths and weaknesses (Voulgaris and Trowbridge, 1997). We have measured major terms in the turbulent kinetic energy (TKE) budget and their variations with time and governing parameters like the gradient Richardson number Ri_g as part of D. J. Kay's thesis (e.g., Figure 2). We have also estimated the mixing efficiency for estuarine interfacial layers.

Further results are viewable at http://www.ccalmr.ogi.edu/res_act.html.

IMPACTS/APPLICATIONS

1. The CWT analysis methods devised in this project should be widely applicable to analyses of non-stationary tidal phenomena and also to the problem of optimal extraction of frequencies from a short record. Together, these circumstances constitute a large percentage of all applications of tidal analysis. CWTs can also provide a consistent analysis of tidal and subtidal variance very difficult to carry out with harmonic analysis.

2. Understanding optical and acoustic properties in the littoral requires a unified approach to physical and ecosystem dynamics, because littoral ecosystems are so strongly forced by advection and mixing. In this regard, the collaborative approach of the Tidal Channels project with other research funded by ONR and the National Science Foundation can serve as a good model.

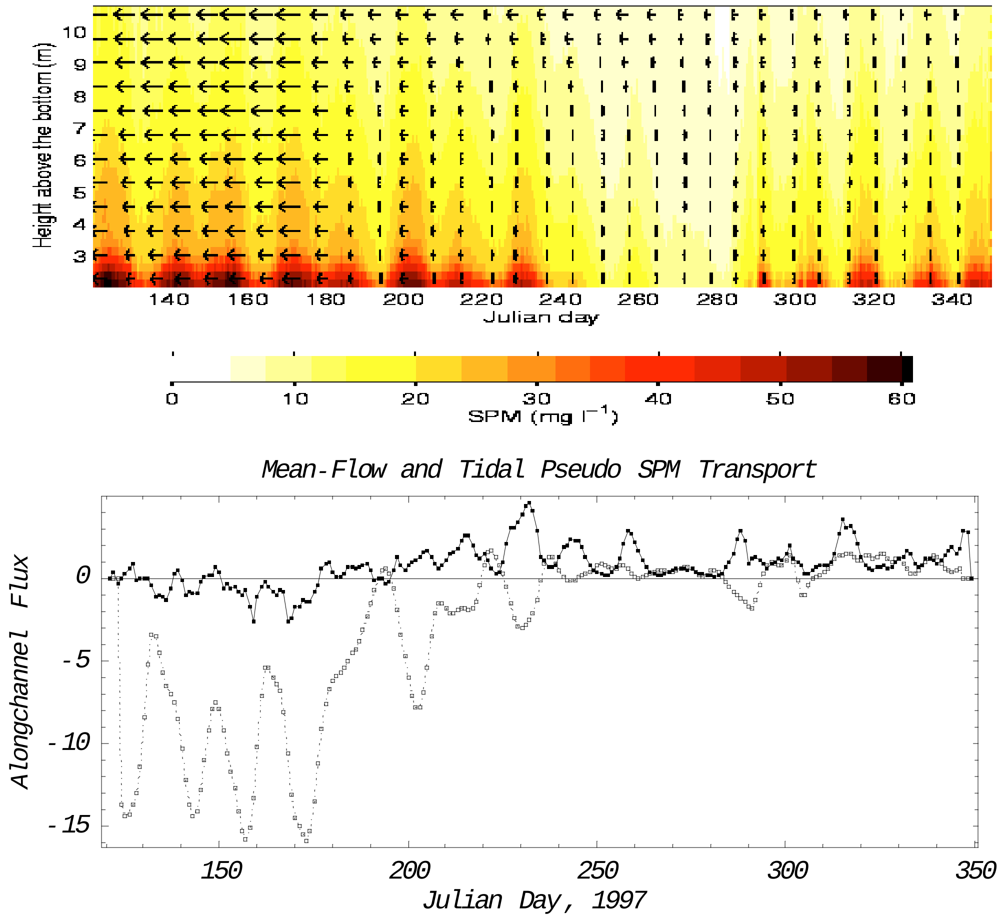

Figure 1: Above: SPM from acoustic backscatter (color-scale) and sub-tidal alongchannel flow (longest arrow is –0.36 ms^{-1}) at Tansy Pt ADP from May to December 1997 as a function of depth. There is an order of magnitude more SPM during the spring freshet (~d 130-170) than during the fall low-flow period (~d 240-285). SPM values increase again during the fall in association with storms. Neap-spring variations in SPM are prominent throughout the record, except ~d 240-285. Below:non-tidal near-bed SPM transport from CWT analysis: sum of major tidal species ( ) and mean-flow transports ( ). Net transport is outward during the spring freshet, particularly on spring tides, and landward otherwise.

3. The three-layer internal hydraulics model and the semi-analytical 3-D profile modeling approach being developed under this project should be widely applicable to other estuaries and shouldmaterially improve our understanding of estuarine circulation.

4. The analyses of vertical turbulent mixing processes should provide an improvement in qualitative understanding of turbulent mixing processes, as well as suggesting methods by which numerical model procedures might be improved.

5. The calibration of ADV and ADP backscatter using the latest methods suggested by the manufacturer (SonTek, 1998) should provide a valuable method for estimating horizontal and vertical SPM fluxes. This approach is especially valuable when combined with CWT analysis methods, so that the dominant transport processes may be determined.

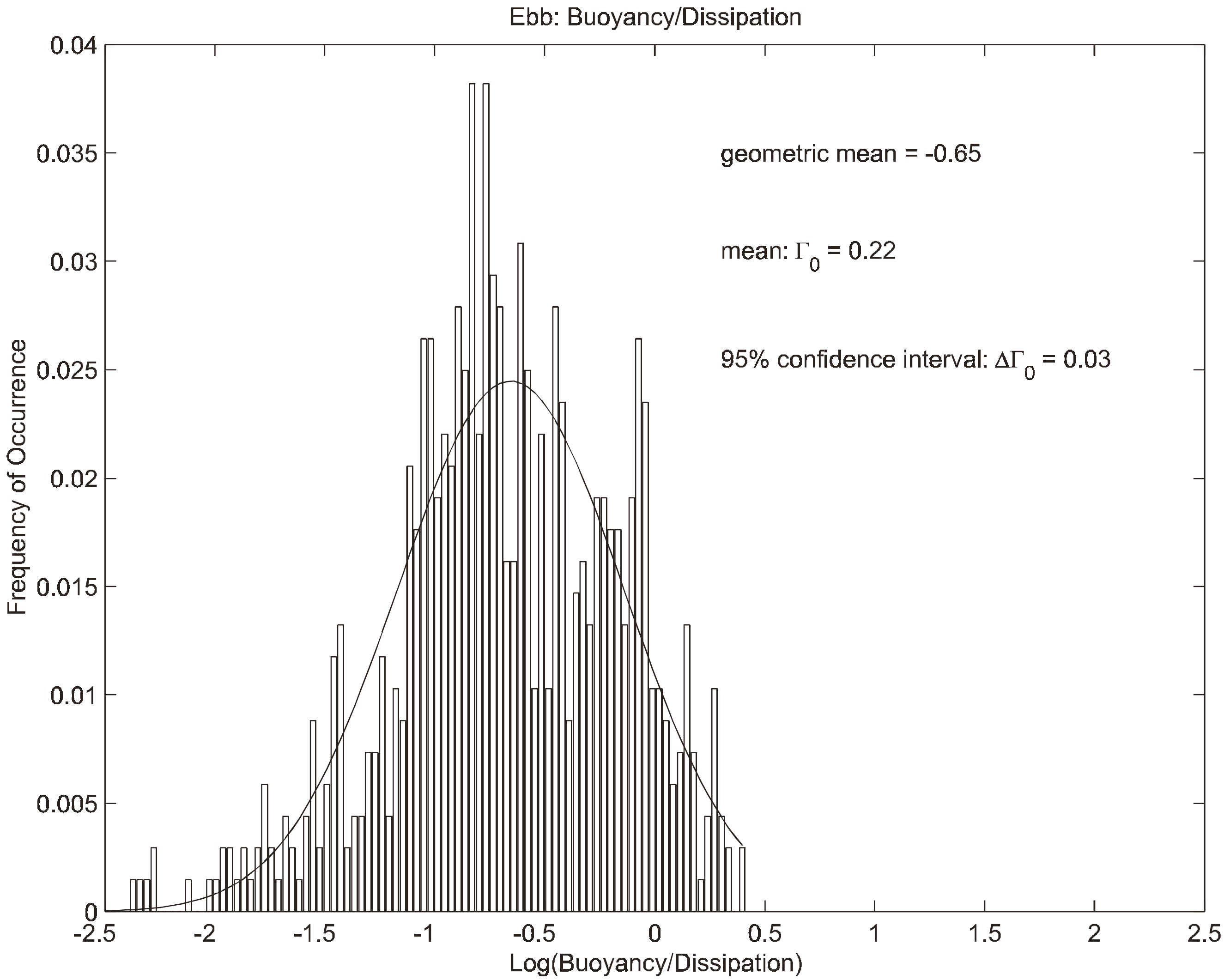

Figure 2: Estimation of the mixing efficiency $_0$ *from ADV and CTD measurements in an estuarine interfacial shear layer using a log-normal distribution;* $_0$ *is found here to be ~0.22 0.03.*

TRANSITIONS

Two CWT tidal analysis programs with sample data sets illustrating their use have been placed on the PI's web page (see CWT software heading under http://www.ccalmr.ogi.edu/ ~djay). Dr. R. Signell of the US Geological Survey has set up a link to these programs on his Sea-Mat web site (http://crusty.er.usgs.gov/sea-mat), to make the programs more widely available to the research community.

RELATED PROJECTS

Work for the Tidal Channels project has been coordinated with the National Science Foundation Columbia River Land-Margin Ecosystem Research (LMER) Program and with the Oceanographic and Environmental Characterization of Coastal Regions (OECCR) funded by ONR. SPM transport ideas developed here and through LMER have led to the hypothesis that estuaries amplify climate signals through their sediment budget. This idea is being pursued through a funded NSF Small Grant for Exploratory Research.

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